

Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils

Citation for published version:

Connolly, D, Kouroussis, G, Woodward, PK, Giannopoulos, A, Verlinden, O & Forde, MC 2014, 'Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils', *Soil Dynamics and Earthquake Engineering*, vol. 66, pp. 78-88. <https://doi.org/10.1016/j.soildyn.2014.06.021>

Digital Object Identifier (DOI):

[10.1016/j.soildyn.2014.06.021](https://doi.org/10.1016/j.soildyn.2014.06.021)

Link:

[Link to publication record in Heriot-Watt Research Portal](#)

Document Version:

Early version, also known as pre-print

Published In:

Soil Dynamics and Earthquake Engineering

General rights

Copyright for the publications made accessible via Heriot-Watt Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

Heriot-Watt University has made every reasonable effort to ensure that the content in Heriot-Watt Research Portal complies with UK legislation. If you believe that the public display of this file breaches copyright please contact open.access@hw.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils

D.P. Connolly (corresponding author)¹, G. Kouroussis², P.K. Woodward¹, A. Giannopoulos¹, O. Verlinden², M.C. Forde³

Abstract

This paper outlines a vibration prediction tool, ScopeRail, capable of predicting in-door noise and vibration, within structures in close proximity to high speed railway lines. The tool is designed to rapidly predict vibration levels over large track distances, while using historical soil information to increase accuracy. Model results are compared to an alternative, commonly used, scoping model and it is found that ScopeRail offers higher accuracy predictions. This increased accuracy can potentially reduce the cost of vibration environmental impact assessments for new high speed rail lines.

To develop the tool, a three-dimensional finite element model is first outlined capable of simulating vibration generation and propagation from high speed rail lines. A vast array of model permutations are computed to assess the effect of each input parameter on absolute ground vibration levels. These relations are analysed using a machine learning approach, resulting in a model that can instantly predict ground vibration levels in the presence of different train speeds and soil profiles. Then a collection of empirical factors are coupled with the model to allow for the prediction of structural vibration and in-door noise in buildings located near high speed lines. Additional factors are also used to enable the prediction of vibrations in the presence of abatement measures (e.g. ballast mats and floating slab tracks) and additional excitation mechanisms (e.g. wheel flats and switches/crossings).

1. D.P. Connolly and P.K. Woodward, Heriot-Watt University, Edinburgh, UK

2. G. Kouroussis and O. Verlinden. Department of Theoretical Mechanics, Dynamics and Vibrations, University of Mons, Belgium

3. M.C. Forde and A. Giannopoulos, University of Edinburgh, Edinburgh, UK

KEYWORDS:

ScopeRail, High speed rail vibration, Environmental Impact Assessment (EIA), initial vibration assessment, structural vibration, in-door noise, scoping assessment, high speed train, urban railway

Highlights

Railway vibration scoping model developed to predict velocity decibel (VdB) levels

Model predicts ground/structural vibration and indoor noise for different soil types

Sub-model developed to utilize historical soil data for scoping vibration assessment

Model coupled to empirical factors to assess mitigation - ballast mats and floating slab

Model validated using 3 test sites and shown to outperform an alternative approach

1. Introduction

The rapid deployment of high speed rail (HSR) infrastructure has led to an increased number of properties and structures being located in close proximity to high speed rail lines (Carels, Ophalffens, & Vogiatzis, 2012), (D. P Connolly, Kouroussis, Laghrouche, Ho, & Forde, 2014). In comparison to traditional inter-city rail, HSR speeds can potentially generate elevated levels of vibration both within the track structure and in the free field. In the free field these vibrations can impact negatively on the local environment, causing properties to shake and walls/floors to generate indoor noise. This can result in personal distress to those inhabiting such properties, and in the loss of building functionality (e.g. for buildings sensitive to vibration such as hospitals, manufacturing industries and places of worship (K Vogiatzis, 2010)).

Therefore in many countries, before a new line is constructed, it is compulsory to undertake a vibration assessment exercise to identify the stakeholders that may experience negative side-effects. To determine these stakeholders as early as possible, the vibration levels from a new line must be calculated at the design stage. With the aim of predicting vibration levels, much research has been undertaken into the analysis of moving loads on a half-space (Fryba, 1972), (Kenney, 1954), (Andersen, Nielsen, & Krenk, 2007). Alternatively, (Krylov, 1995) proposed a frequency domain model that accounted for the contribution of each sleeper on the vibration field, and used Greens functions to model ground wave propagation effects.

Alternative frequency domain approaches have since been proposed by (Sheng, Jones, & Petyt, 1999), (Sheng, Jones, & Thompson, 2004) and (Konstantinos Vogiatzis, 2012) which used a combination of transfer functions for the train, track and soil to calculate vibration levels, and at large distances from the track. (Auersch, 2012) also used transfer functions to model the effect of moving loads and vibration through a layered soil.

Other frequency domain approaches were presented by (M. F. M. Hussein & Hunt, 2009) and (M. F. M. Hussein & Hunt, 2007) who used the pipe-in-pipe (PiP) method to predict vibration levels for underground railway lines. (Chebli, Othman, Clouteau, Arnst, & Degrande, 2008), (Sheng, Jones, & Thompson, 2006) and (Galvin, Romero, & Domínguez, 2010) also presented a three dimensional (3D) approach to modelling train passage using a combination of the finite element (FE) and boundary element (BE) method. The suitability of both the 3D FE-BE formulations and PiP approaches were compared and found to perform well (Gupta, Hussein, Degrande, Hunt, & Clouteau, 2007).

Several time domain formulations have also been proposed for simulating railway vibration. Although work has been undertaken to adapt the finite difference time domain (FDTD) method for moving load problems (Thornely-Taylor, 2004), (Katou,

Matsuoka, Yoshioka, Sanada, & Miyoshi, 2008), the majority of research has been performed using the FE method (and the coupled FE-BE method (Mulliken & Rizos, 2012)). Recently (Yang, Powrie, & Priest, 2009) presented a 2D FE analysis to determine the effect of train speed on track characteristics. An alternative, advanced 3D model was presented by (Kouroussis, Verlinden, & Conti, 2011) who used a sub-structuring approach to model the propagation of vibration through the track, track and soil. Similarly, (El Kacimi, Woodward, Laghrouche, & Medero, 2013) used a fully 3D FE model to model vibrations from moving trains and analysed the effect of critical velocities. Lastly, (D. Connolly, Giannopoulos, & Forde, 2013) used a fully 3D FE approach to facilitate the modelling of the complex track geometry and its contribution to railway vibration levels.

A challenge with both numerical frequency domain and numerical time domain models is that their computational run times are prohibitive for initial scoping assessment. If large sections of railway track require analysis then it is vital that predictions can be made with low computational effort.

In an attempt to achieve this, (Rossi & Nicolini, 2003) proposed a straightforward mathematical tool to rapidly predict soil absolute vibration velocity levels in decibels and root mean squared values. The model only considered the contribution of Rayleigh waves in its solution and the track was considered as a continuous structure. Results were compared to field results obtained in (Harris, Miller, & Hanson, 1996) and it was found that the modelling accuracy was comparable to more computationally demanding numerical approaches.

An alternative model also based on the data collected in (Harris et al., 1996) was developed by (Federal Railroad Administration, 2012) to predict absolute vibrations from high speed rail lines. This empirical approach used curve fitting techniques to develop relationships between train speed and distance from the track, with geological conditions largely ignored. This curve was then adjusted based on empirically derived factors to account for changes in soil-building coupling and track configuration.

This paper presents an empirically based model (ScopeRail) that builds upon (D. P Connolly, Kouroussis, Giannopoulos, et al., 2014) to facilitate the prediction of vibration decibels, in the presence of variable track-forms and in multiple building types. Furthermore, new SPT relationships are defined to convert historical soil data into model input data. The model uses a machine learning approach to approximate relationships for the effect of soil layering on vibration transmission. These relationships are then combined with empirical factors to facilitate rapid vibration prediction for a wide array of track and building characteristics. ScopeRail is then compared to the performance of the original (Federal Railroad Administration, 2012) approach and it is found to offer enhanced performance.

2. MODELLING PHILOSOPHY

Railway vibration scoping models are used to assess vibration levels quickly and efficiently during the planning stage of a new line. Their goal is to predict vibration levels across large sections of track (in a conservative manner) to identify key areas that are likely to be effected by elevated vibration levels. Then these areas can then be investigated further using more in-depth analysis. To predict vibration levels over wide areas it is vital that scoping models can be deployed with minimal computational requirements. With this in mind, accuracy is sometimes sacrificed in preference for reduced computational requirements. This means that vibration levels can be often overestimated and that detailed analysis is performed in areas where it was not required. Detailed railway vibration analyses are cost intensive and therefore this results in unnecessary additional project costs.

In addition to computational requirements and prediction accuracy, both parameter availability and usability are important considerations when deploying a scoping vibration prediction model. Usability is important from a practical point of view because a model that has a long learning curve or requires extensive prior engineering knowledge. Similarly, the model output must be compatible with the existing vibration standards governing the project. Similarly, parameter availability is important because if highly detailed soil information is needed for large areas then field experiments may be required which is undesirable. Instead, for scoping assessment, it is more advantageous to utilise rudimentary soil information in the form of historical records, where possible, to quickly determine a simplified soil profile. For high speed lines, the process of gathering historical soil data is performed at an early stage (for track dynamics purposes) and therefore can also be utilised within a ground vibration prediction model. These four equally desirable scoping model characteristics are outlined in Figure 1.

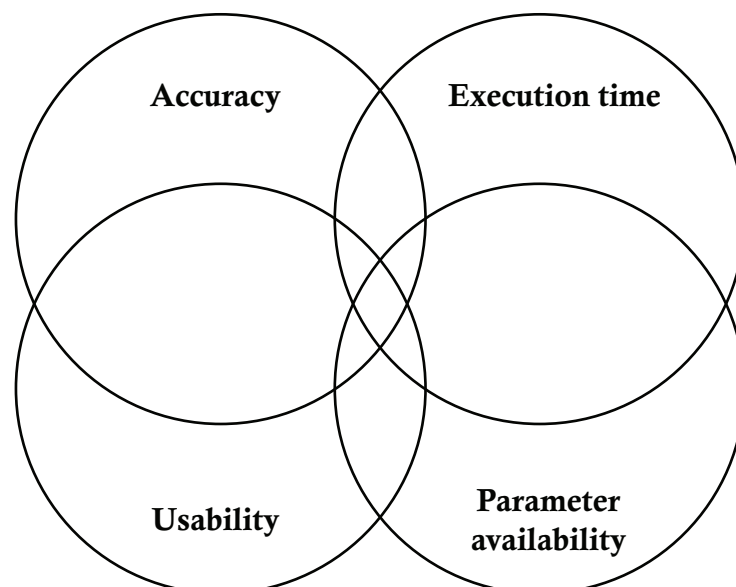


Figure 1 – Vibration prediction models - development considerations

3. MODELLING APPROACH

The modelling approach used to develop ScopeRail was composed of two distinct parts. Firstly a FE model was developed that was capable of predicting high speed railway ground-borne vibration time histories. This model was then computed many times to build up a database of velocity time histories for different soil conditions, train speeds and distances from the track. The second step involved a statistical analysis of results using a machine learning approach to achieve a model that could quickly and accurately predict vibration levels in the presence of varying soil conditions.

3.1 FE model development

The finite element model consisted of three distinct, fully coupled components to describe the train, track and soil respectively. All components had one axis of symmetry and therefore only half of each required modelling. The soil was modelled using linear elastic, eight noded, three dimensional brick elements with dimensions 0.3m in each direction. Four of the six soil boundaries were truncated using infinite elements, described using an exponential decay function to simulate an infinitely long domain. The top boundary was the location of the free surface and the horizontal displacement was constrained in the direction perpendicular to the track thus accounting for the soil symmetry. Rather than utilise a spherical geometry ((D. Connolly, Giannopoulos, & Forde, 2013), (Kouroussis et al., 2011)) to improve infinite element performance, a uniformly meshed rectangular model was preferred.

The track model was fully three dimensional (Figure 2) thus allowing for the simulation of the complex geometries associated with its structure. This overcame some of the assumptions associated with the simplified track modelling approaches as presented by (Kouroussis et al., 2011), (El Kacimi et al., 2013). Therefore the transmission of forces between each track component was simulated in a realistic manner. The track conformed to the layout commonly found on high speed rail lines in mainland Europe and was constructed from subgrade, subballast and ballast layers, supporting evenly spaced sleepers at 0.6m spacings. The rail was connected to the sleepers and modelled using 0.1m long beam elements. The track material properties are show in Table 1.

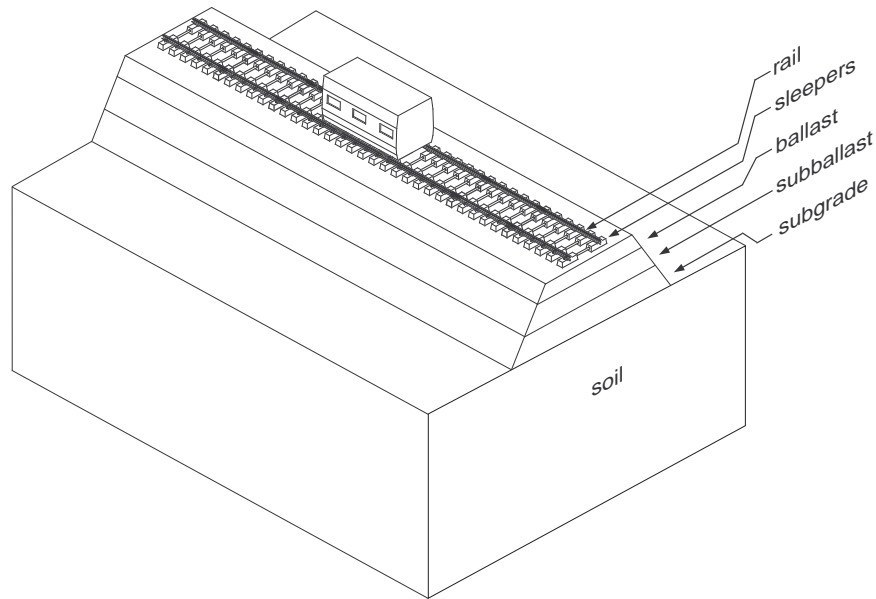


Figure 2 – FE model schematic

	Young's modulus (MPa)	Poisson's ratio	Density (kg/m ³)	Layer thickness (m)
Rail	210,000	0.28	7,900	
Sleepers	20,000	0.25	2,400	
Ballast	200	0.3	1600	0.3
Subballast	130	0.3	2000	0.2
Subgrade	90	0.3	2000	0.5

Table 1 – Track material properties

The vehicle was modelled using a lumped mass, multi-body dynamics approach. Three masses were used to simulate the car, bogie and wheel respectively, and were connected using spring/damper elements. Although the soil and track equations of motion were developed directly using the commercial FE software ABAQUS, the equations of motion for the vehicle were written manually and then coupled with the ABAQUS solver. This allowed for an efficient method to compute the force input to the track and for the wheel to be coupled with the rail using a non-linear Hertzian spring as described in ((Johnson, 1985), (D. Connolly, Giannopoulos, Fan, Woodward, & Forde, 2013)). The vehicle model and coupling mechanism is shown in Figure 3. The vehicle was assumed to be a Thalys high speed train with properties as defined in (Kouroussis, Connolly, & Verlinden, 2014)

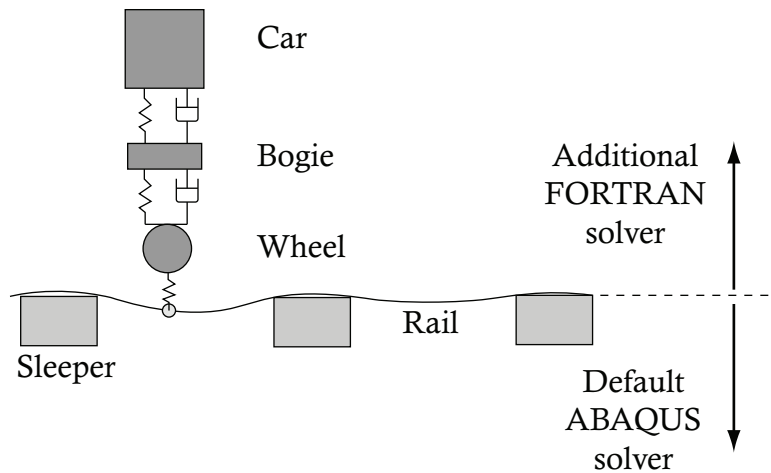


Figure 3 – Vehicle model and coupling mechanism

3.2 ScopeRail model development

Although the FE model could model railway tracks in detail and was able to predict vibration time histories, its run times were too long for it to be used for railway vibration scoping assessments. Therefore it was used as the basis to develop another model, with much lower computational demands, known as ScopeRail. To do so, a machine learning approach was used in an attempt to map train, track and soil characteristics to resultant absolute ground vibration levels.

Firstly, a sensitivity analysis was undertaken to determine the most influential parameters that contributed to the generation of ground borne vibration from rail lines. The least influential parameters and those with large standard deviations (e.g. wheel/rail defects) were excluded from model development. A more detailed explanation of these tests can be found in (D. P Connolly, Kouroussis, Giannopoulos, et al., 2014), (D. P Connolly, Peters, Sim, et al., 2014).

One of the most important parameters affecting ground vibration propagation is soil characteristics (Auersch, 2012). To include soil properties within the scoping model, two alternative approaches were undertaken. The first approach was to consider the soil as a homogenous half space (i.e. a single layer) and the second was to consider the soil as a two layer medium. It should be noted that although an infinite number of soil configurations exist in practice, for the purpose of a scoping model, a limited number of input parameters was desirable. This was because it is difficult to obtain detailed soil information for large geographical areas. Therefore, extending the model to three or more layers was considered undesirable. The key input/output model parameters for the one layer and two layer cases are shown in Figure 4 and Figure 5 respectively.

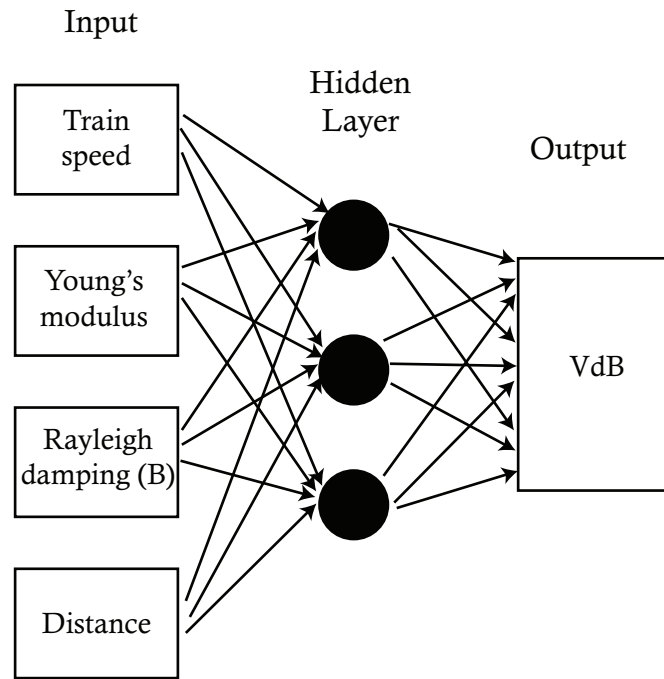


Figure 4 – One layer neural network schematic

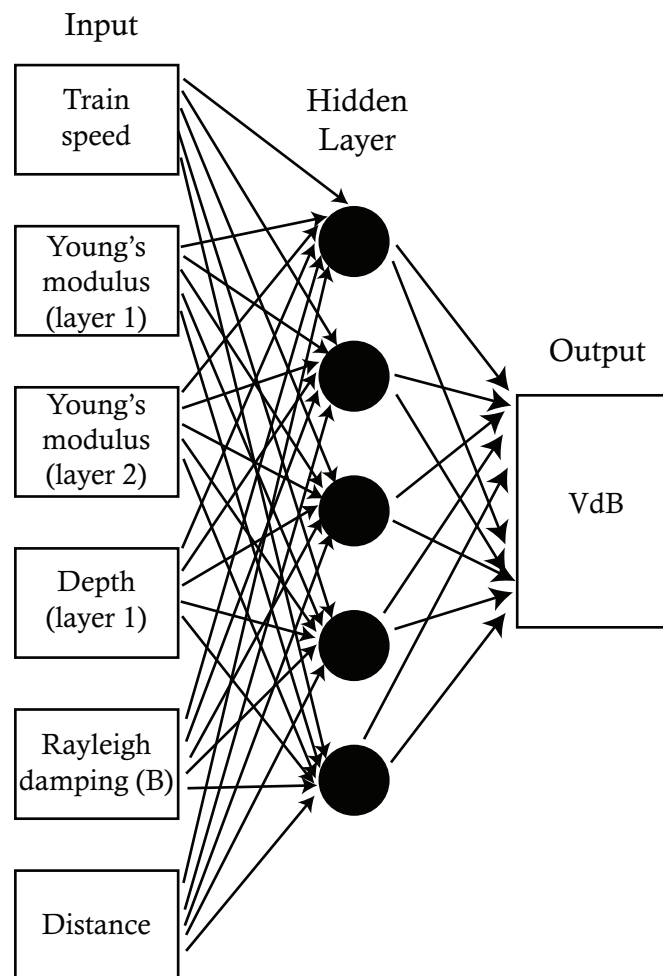


Figure 5 – Two layer neural network schematic

3.3 Vibration metrics

The complexity of seismic wave propagation prohibited the prediction of raw time history signals using machine learning. Instead, key vibration indicators were calculated using raw ABAQUS model vibration time histories and then used as the outputs/targets for neural network construction.

Many national and international metrics have been proposed for railway vibration assessment (Table 2). A challenge with their use is that each standard uses different criteria to assess vibration levels making it difficult to compare standards and to classify vibration levels universally. For example, the UK and Spain use acceleration to quantify vibration whereas Germany and America use velocity criteria. Similar differences exist between frequency weighting curves, time averaging procedures, units of measurement and metrics. Comprehensive reviews of existing standards can be found in (Griffin, 1998) and (Elias & Villot, 2011).

Although the scoping model outlined in (D. P Connolly, Kouroussis, Giannopoulos, et al., 2014) was capable of predicting KB_{fmax} (Deutsches Institut für Normung, 1999) and PPV values, these were less compatible with empirical vibration relationships used to convert ground vibration into indoor noise. Therefore, with the ultimate aim of maximising compatibility and usability, ScopeRail was redeveloped to predict vibration decibels (VdB_{max} - hereafter denoted simply VdB) as outlined in (Federal Railroad Administration, 2012). VdB was a logarithmic based vibration scale, with the maximum value offering a useful individual absolute measurement of vibration. It was calculated using Equation 1, where V_{rms} was the moving average of the raw velocity time history, calculated over a one second time period ('slow' setting). V_0 was the reference level of background vibration, for which a constant value of 2.54×10^{-6} m/s was chosen.

$$VdB = 20 \log_{10} \frac{v_{rms}}{v_0} \quad \text{Equation 1}$$

Country	Relevant standard(s)	Country	Relevant standard(s)
Austria	ONORM 9012:2010	Spain	Real Decreto 1307/2007
Germany	DIN 4150-2:1999	Sweden	SS 460 48 61:1992
Italy	UNI 9614:1990	UK	BS 6472-1:2008, BS 7385-2:1993

Netherlands	SBR Richtlijn - Deel B (2002)	USA	FRA (2012), FTA (2006)
Norway	NS 8176:2005	International	ISO 2631-1:1997, ISO 2631-2:2003

Table 2 - National and international vibration standards. (Recreated from (Elias & Villot, 2011)).

4. Using historical soil data within a scoping model

The advantage of ScopeRail over some alternative vibration scoping models was that it was capable of accounting for soil conditions within its prediction. At the vibration scoping stage of a high speed rail project rudimentary soil data is often available as a by-product from track design/selection process. Therefore this information can be reused within a scoping model. Despite this, if a comprehensive record of soil data is not available then it may be necessary to construct soil profiles manually from historical information. These historical records usually relate to tests such as borehole logs and SPT, which are not directly compatible with the properties required to model wave propagation. Therefore, it is difficult to utilise historical data within previously developed models such as (D. P Connolly, Kouroussis, Giannopoulos, et al., 2014).

To overcome this, a variety of previously proposed empirical relationships were investigated for the purpose of mapping the most common types of exiting historical test records to wave propagation parameters. These relationships were used to develop a range of new equations, which were then incorporated within ScopeRail.

4.1 Utilising historical SPT data

An advantage of using Standard Penetration Test (SPT) N-values to determine FE modelling properties is that historically the SPT test has been the most widely performed test and national resources such as ("British Geological Association," 2013) provide an extensive database of borehole logs. Therefore it is often possible to obtain SPT data without the financial outlay required to perform physical tests.

Additionally, a wide body of research exists for correlating SPT N-values with physical soil properties. Therefore it is possible to use SPT data to obtain soil properties that are more reliable than using soil only description data. Despite this, a challenge with the SPT test is that the methodology is not performed consistently and parameters such as the drop height can vary between countries. (Robertson, Campanella, & Wightman, 1983) presented correction factors to account for these inconsistencies although some authors have questioned whether these factors lead to more reliable results. Additionally, it should be noted that all SPT N-value correlations

are based on soils experiencing low strain levels (i.e. the assumption of small strain theory).

Figure 6 presents correlations between SPT N-values and shear wave speeds for general soils. The overall deviation between correlations is low, apart from (Seed, Idriss, & Arango, 1983) and (Iyisan, 1996), which both seem to overestimate shear wave velocity.

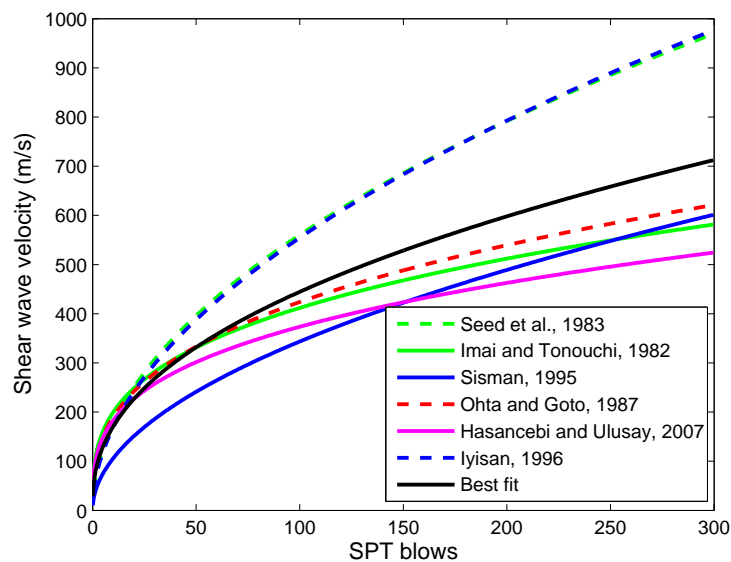


Figure 6 - SPT shear wave velocity correlations – all soils. (Seed et al., 1983), (Imai & Tonouchi, 1982), (Sisman, 1995), (Ohta & Goto, 1978), (Hasancebi & Ulusay, 2006), (Iyisan, 1996)

Rather than use SPT correlations to classify all generic soil types, empirical relationships have also been presented for individual soil types. Each of these is based upon whether the soil is a sand, clay or silt; information which is typically recorded when performing SPT testing.

Figure 7, Figure 8 and Figure 9 show relationships for sand, silt and clay respectively. For each soil type, relationships are relatively well correlated with each alternative relationship. Exceptions are the relationships proposed by (Jafari, Shafiee, & Razmkhah, 2002), which for each soil, overestimates the shear wave velocity.

In addition to the relationships shown in Figure 6 - Figure 9, authors such as (Seed, Wong, Idriss, & Tokimatsu, 1987) have proposed correlations based on a greater number of variables (e.g. soil depth) in attempt to improve accuracy.

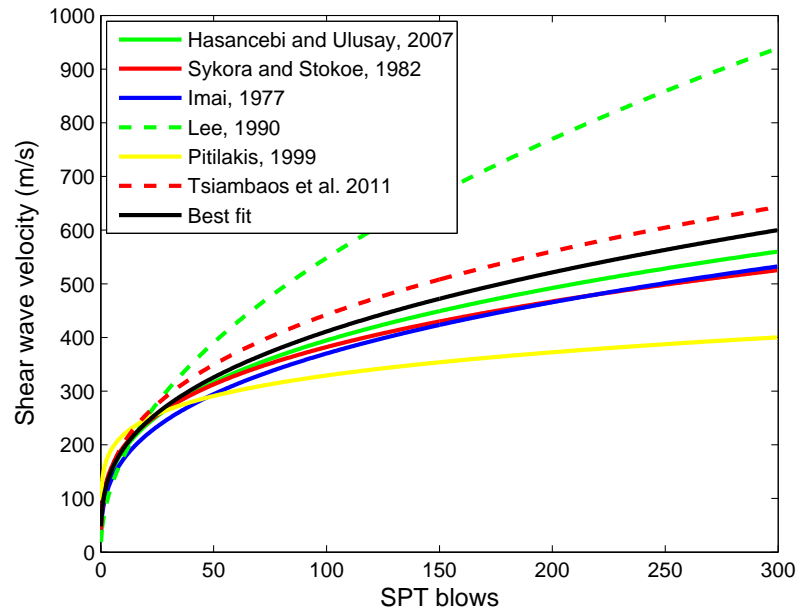


Figure 7 - SPT correlations – Sand. (Hasancebi & Ulusay, 2006), (Imai, 1977), (S. Lee, 1990), (S. Lee, 1990), (Pitilakis, Raptakis, Lontzetidis, & T, 1999), (Tsiambaos & Sabatakakis, 2010)

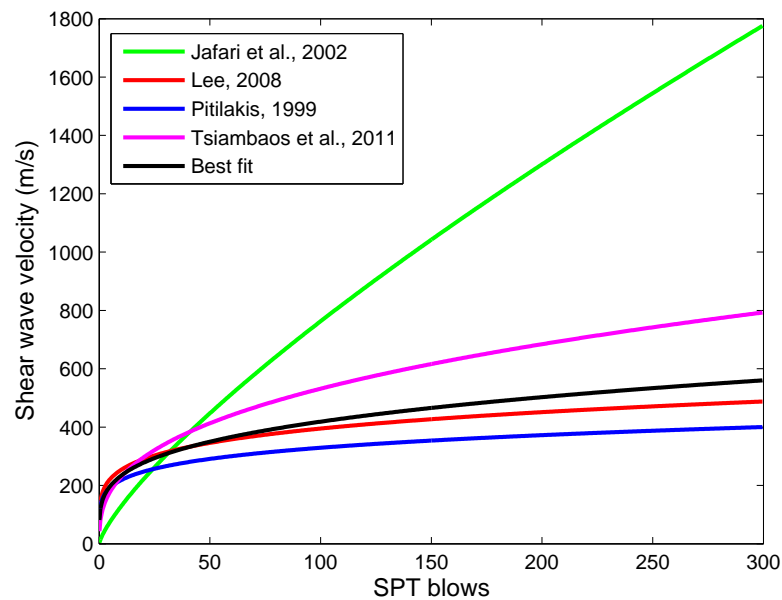


Figure 8 - SPT correlations – Silt. (Jafari et al., 2002), (C. Lee & Tsai, 2008), (Pitilakis et al., 1999), (Tsiambaos & Sabatakakis, 2010)

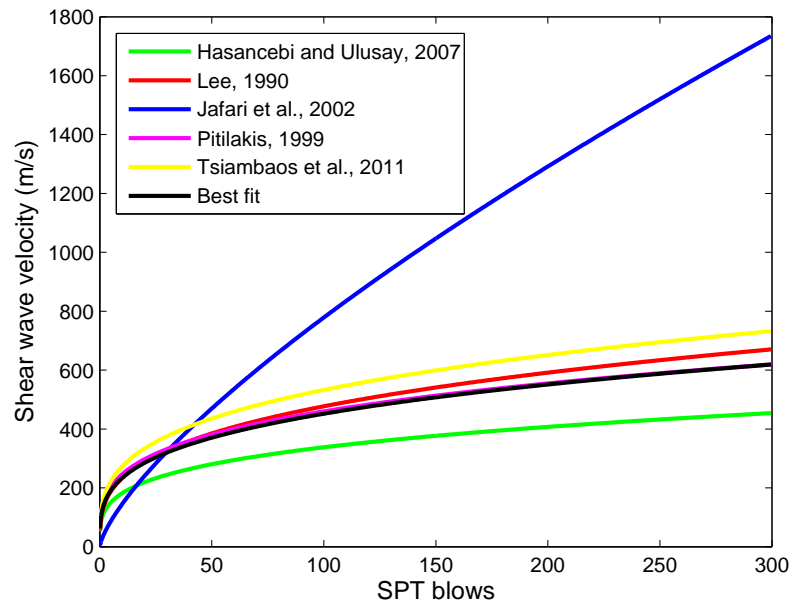


Figure 9 - SPT correlations – Clay. (Hasancebi & Ulusay, 2006), (S. Lee, 1990), (Jafari et al., 2002), (Pitilakis et al., 1999), (Tsiambaos & Sabatakakis, 2010)

Rather than attempt to utilise a variety of SPT relationships, one new relationship for each soil type was developed. These new relationships were best fit correlations between all other relationships and are shown using a black line in Figure 6 - Figure 9. For both the silt and clay relationships, the equations presented by (Jafari et al., 2002) were ignored because they exhibited a poor correlation with all other proposed relationships. The new relationships are described numerically in Table 3 and plotted in Figure 10. As expected, the SPT relationships proposed for generic soil shear wave speeds had the largest standard deviation. Silts had a relatively large standard deviation and clays had the lowest at 64.5m/s.

Soil type	SPT relationship	Standard deviation (m/s)
General soils	$V_s = 62.9 \cdot N^{0.425}$	111.7
Sands	$V_s = 86.71 \cdot N^{0.3386}$	81.6
Clays	$V_s = 120.8 \cdot N^{0.2865}$	64.5
Silts	$V_s = 127.1 \cdot N^{0.2595}$	102.9

Table 3 - Best fit SPT 'N-value' correlations

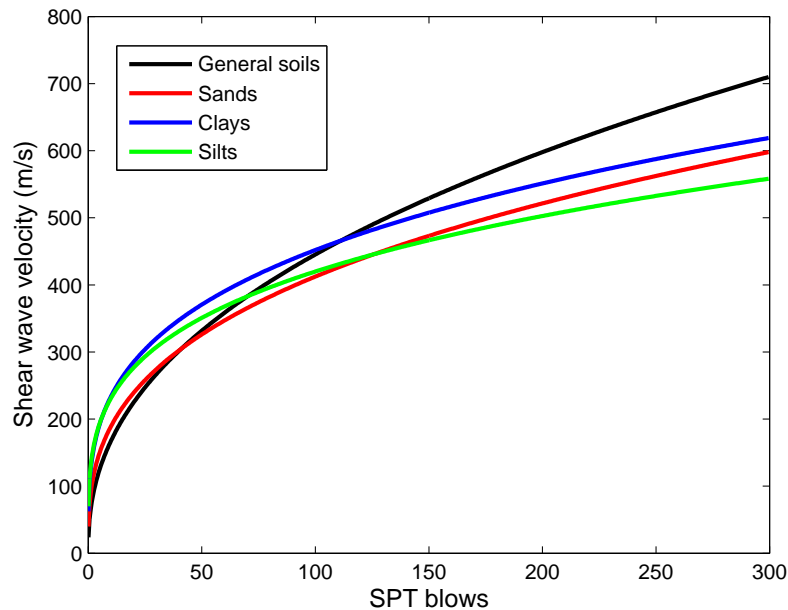


Figure 10 - Best fit SPT 'N-value' correlations

4.2 Utilising historical CPT data

The Cone Penetration Test (CPT) test is an alternative and more sophisticated penetration experiment in which a metal cone is pushed into soil and the penetrative resistance (q_c) is measured. The cone typically has a diameter of 35.7mm², cast at a 60° angle and is pushed, with the aid of a land vehicle, into the soil at a constant rate.

In addition to cone tip resistance, sleeve friction (f_s) is commonly measured. Less commonly, piezocone penetration tests are used to measure pore water pressure and sometimes seismic cone penetration tests are used to measure shear wave velocity.

Although CPT testing is becoming more widespread, SPT testing remains more common place and historical data relating to SPT N-values is more freely available. One explanation for this is that due to the force required to push the cone into soils, the CPT method can only be used for relatively soft soils. Therefore researchers such as (Chin, Duann, & Kao, 1988) have attempted to correlate CPT results with SPT N-values. This approach is not recommended for the purpose of using empirical correlations to estimate FE parameters because it creates an additional layer of uncertainty. Instead, several authors have presented formulations based directly on CPT results, a variety of which are shown in Table 4.

For these relationships, σ is effective stress, ' k_2 ' is a coefficient function of relative density, ' q_t ' is the corrected cone tip resistance (Dejong, 2007) and ' e_0 ' is void ratio. The relationships have not been plotted graphically because of their dependence on a variety of soil parameters. This makes it challenging to make direct comparisons.

Soil property	Equation	Soil type	Reference
Shear modulus	$1000 \cdot k_2 \cdot \sigma^{0.5}$	Sand	(Paoletti, Hegazy, Monaco, & Piva, 2010)
Shear wave velocity	$50 \cdot ((q_c/p_a)^{0.43} - 3)$	Sand	(Paoletti et al., 2010)
Shear wave velocity	$277 \cdot q_t^{0.13} \cdot \sigma^{0.27}$	Sand	(Baldi, Bellotti, Ghionna, Jamiolkowski, & Presti, 1989)
Shear wave velocity	$(10.1 \cdot \log(q_t) - 11.4)^{1.67} \cdot (f_s/q_t \cdot 100)^{0.3}$	General soils	(Hegazy & Mayne, 1995)
Shear wave velocity	$118.8 \cdot \log(f_s) + 18.5$	General soils	(Mayne, 2006)
Shear wave velocity	$1.75 \cdot q_t^{0.627}$	Clay	(Mayne & Rix, 1995)
Shear wave velocity	$9.44 \cdot q_t^{0.435} \cdot e_0^{-0.532}$	Clay	(Mayne & Rix, 1993)
Shear wave velocity	$1.75 \cdot q_t^{0.627}$	Clay	(Mayne & Rix, 1993)

Table 4 - CPT empirical relationships

4.3 Utilising historical laboratory data

Lab testing involves extracting soil samples from the test site, transporting them to the lab and performing controlled experiments to determine characteristics that are difficult to obtain using in-situ tests.

A variety of lab testing methodologies are available including bender element testing, resonant column testing, ultrasonic pulse testing and more traditionally, tri-axial testing.

A major advantage of lab testing is that the samples are tested under controlled conditions and therefore allow for a more accurate determination of soil properties. Despite this, due to inevitable sample disturbances caused during soil sample extraction and transportation, the properties of a soil at the time of lab testing are not always similar to the properties of the soil in-situ.

Classical lab testing refers to tests such as the quick undrained triaxial test to determine undrained shear strength (Dickensen, 1994). They also include other tests to determine properties such as bulk density, moisture content, liquid limit and plastic limit. Although these soil properties (except density) are not required for FE simulation, correlations have been proposed to map them more closely to parameters such as Young's modulus (Houbrechts et al., 2011).

For vibration prediction purposes, it is sometimes the case that classical lab testing data is available in addition to existing borehole data. Therefore empirical correlations between lab data and FE parameters may be useful for validating SPT correlations. Despite this, if a new soil lab investigation is being performed then bender element and resonant column testing techniques are preferable to classical lab testing. This is because the aforementioned tests can determine FE parameters directly, rather than approximating them using empirical relationships.

One of the most common empirical relationships between lab test results and shear modulus is:

$$\mu = AF(e_0)(\sigma'_0)^n \quad \text{Equation 1}$$

$F(e_0)$ is a function of the void ratio, σ'_0 is the effective confining stress and n is non-dimensional. A range of suggested values based on Equation 1, for a range of void ratios are shown in Figure 11. I_p is the plasticity index associated with each sample. The effective confining stress for each relationship was assumed to be 100 kPa.

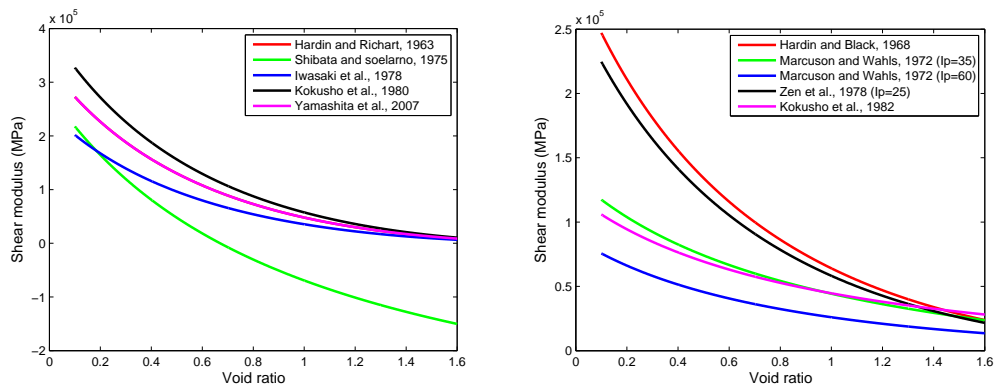


Figure 11 - Empirical void ratio correlations

Equation 1 depends solely on the prior calculation of void ratio and therefore is often used due to its ease of application. Alternatively, researchers have presented formulations which depend on additional experimentally calculated variables. For example, (Larsson & Mulabdic, 1991) outlined a correlation based upon liquid limit and undrained shear strength. Also, (Hardin & Black, 1963) presented a correlation based upon both void ratio and over-consolidation ratio (OCR). Despite this OCR is difficult to accurately determine even through lab testing thus making it difficult for practical use. Some empirical relationships for calculating OCR from CPT results are provided by (Lunne, Robertson, & Powell, 1997).

Damping can also be calculated from classical lab test results with (Kramer, 1996) suggesting it can be calculated using the hysteresis loop for a soil. Alternatively, several authors propose that damping is highly correlated with normalised shear modulus. As discussed previously, vibrations generated due to train passage are in the small strain zone thus allowing (Ishibashi & Zhang, 1993) to propose the relationship:

$$D = 0.0065(1 + e^{-0.0145I_p^{1.3}}) \quad \text{Equation 4.2}$$

This equation is based on solely the plastic modulus (I_p) and has been shown by (Biglari & Ashayeri, 2011) to provide an accurate approximation for a range of soils. Alternative formulations have also been presented by (Rollins, Evans, Diehl, & Daily, 1998) and (Kagawa, 1993), both based on using cyclic shear strain values. Furthermore, (Houbrechts et al., 2011) presented typical damping values for soil (Figure 12).

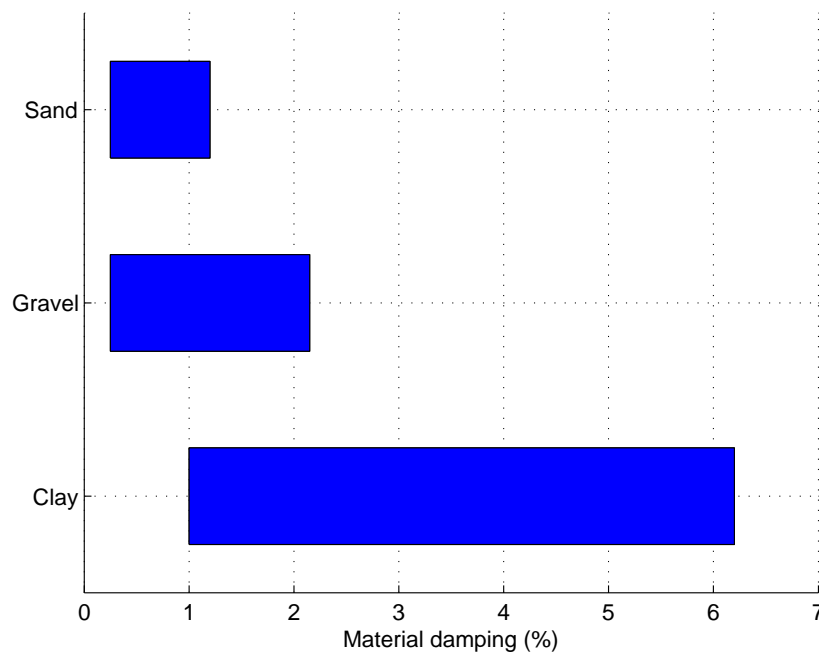


Figure 12 – Typical damping ratios (replicated from (Houbrechts et al., 2011))

4.4 Soil layer mapping

The scoping model was only capable computing a discrete number of input soil layers (2 layers), however typical soil profiles consist of a greater number of layers. Therefore, to enable the model to be used at any test site, the soil property input information was converted into a 2 layer soil. This translation was performed using a straightforward thickness weight average technique:

$$E_{eq} = \frac{\sum H_i E_i}{\sum H_i} \quad \text{Equation 3}$$

where E_{eq} = equivalent Young's modulus, H_i = each layer thickness and E_i = Young's modulus of each layer.

5. Structural vibration, mitigation and excitation factors

The machine learning approach allowed for rapid prediction of ground vibrations in two layered soils. Additionally, the empirical soil relationships allowed for historical soil relationships to be included in the vibration propagation path. Despite this, the upgraded machine learning approach was based upon results obtained from a generic high speed train-track-soil model, and it could only predict absolute vibration levels on a soil surface.

To upgrade ScopeRail versatility from the previously developed approach (D. P Connolly, Kouroussis, Giannopoulos, et al., 2014), and make it applicable to a wider range of track forms and excitation mechanisms, it was combined with empirical modification factors (Federal Railroad Administration, 2012). These factors allowed for the vibration level to be modified to account for elevated excitations generated due to wheel flats, corrugated track and switches/crossings. Similarly, the factors allowed for the vibration levels to be modified to account for ballast mats, floating slabs, resilient fasteners/ties and earthworks profiles. Although more detailed structural factors have been proposed (Auersch, 2010), the use of transfer functions within a scoping model adds undesired complexity. Furthermore, because the (Federal Railroad Administration, 2012) amplification factors were essentially uncoupled, and the vibration metric (VdB) was the same as that used within ScopeRail, the compatibility between methods was high. This facilitated a seamless coupling between the factors and ScopeRail.

Furthermore, as the original FE model was only used to predict ground surface vibration levels rather than building vibrations, the basic ScopeRail model could also only predict ground vibration levels. This is a commonly used approach ((Lombaert & Degrande, 2009), (Kouroussis et al., 2011), (Kattis, Polyzos, & Beskos, 1999), (Sheng et al., 1999), (Galvin et al., 2010), (Auersch, 2012), (Costa, Calçada, & Cardoso, 2012), (O'Brien & Rigos, 2005)) due to the difficulties in determining soil-building coupling characteristics. Although several attempts have been made to include soil-structure coupling within predictions ((Fiala, Degrande, & Augustinovicz, 2007), (M. Hussein, Hunt, Kuo, Costa, & Barbosa, 2013)), these methods are still experimental. To convert the ScopeRail predicted ground vibration levels to structural vibration and in-door noise, empirical modification factors were again used (Federal Railroad Administration, 2012).

It should be noted that the factors related to train speed, distance from the track and geological conditions were not retained from the (Federal Railroad Administration, 2012) procedure. This is because these factors were inherently included within the ScopeRail model. The final factors implemented with ScopeRail are shown in the Appendix.

6. Model validation

6.1 Field work

To ensure that the scoping model was capable of predicting vibration levels for a variety of test sites and that it had not been over-fitted, it was validated using three sets of experimental results. To provide a fair comparison, these field test results were composed of data collected by the authors and also by independent researchers.

The first set of results were recorded in Belgium in 2001 (Degrande & Schillemans, 2001) and thus denoted 'Degrande 2001'. During testing, vibration levels were sampled using accelerometers and then converted to velocity time histories. A more detailed experimental description is found in the original article.

An experimental campaign was also undertaken in 2012 to collect results for the additional comparisons. Firstly, vibrations were recorded on the Paris to Brussels high speed line (David P. Connolly, 2014), (Kouroussis, Connolly, Forde, & Verlinden, 2013), (D. P Connolly, Kouroussis, Fan, et al., 2013) and were denoted 'Mons 2012'. Secondly, vibrations were recorded on the London-Paris high speed line (HS1) and were denoted 'HS1 2012'. Identical equipment was used for both experimental tests, however for the 'Mons 2012' tests, vibrations were measured up to 100m from the track, while for the 'HS1 2012' tests, vibrations were measured up to 35m from the track. For both tests a

multi-channel analysis of surface waves procedure was used to determine the underlying soil properties (Figure 14). For each train passage the train speed was determined during post-processing using a combination of cepstral analysis, dominant frequency analysis and a regression analysis to compare experimental and theoretical frequency spectrum (Kouroussis, Connolly, Forde, & Verlinden, 2014).



Figure 13 – left: 'Mons 2012' test site, Right: 'HS1 2012' test site.

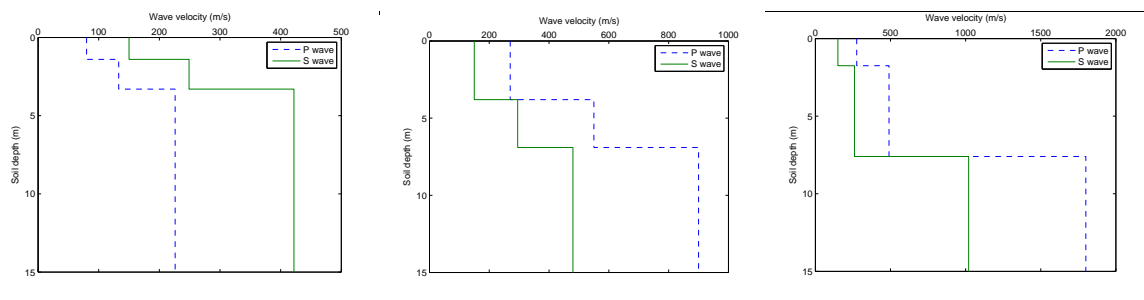


Figure 14 – Compressional and shear wave profiles at test sites, Left: Degrande 2001, Middle: Mons 2012, Right: HS1 2012

6.2 One layer model validation

First the model was tested using a homogenous soil to approximate the layered profile at each test site. To benchmark the model performance against a scoping model that did not include soil properties in its calculation, the results were compared to predictions calculated using the (Federal Railroad Administration, 2012) approach.

Figure 15 shows that the homogenous model performed well and was able to predict VdB values with strong accuracy for each test site. For the Mons 2012 test site ScopeRail closely matched the experimental results. Similar results were found for Degrande 2001 although there was an over prediction of vibration levels for the receivers at distances greater than 10m. For the HS1 2012 results the new model was found to slightly over predict vibration levels at distances less than 20-25m from the track, and to over predict levels at further distances.

A comparison between models revealed that performance was relatively similar, with both models overestimating vibration levels for the majority of receiver locations. For the (Federal Railroad Administration, 2012) calculations, this reflects the anticipated conservative nature of the model. For the Mons 2012 results, ScopeRail was found to offer marginally enhanced performance at large offsets (2-3 dB), and moderately better accuracy for HS1 2012.

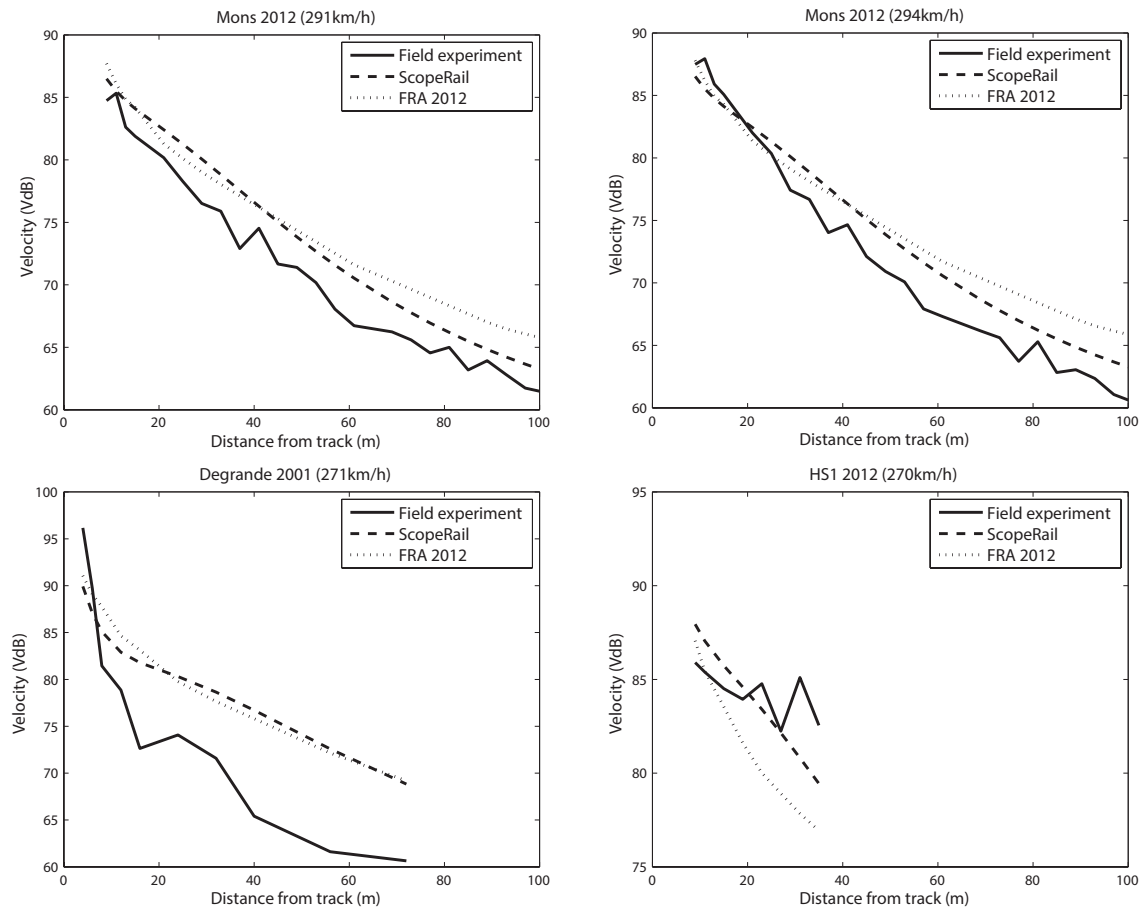


Figure 15 - One layer model performance, Top left: Mons 2012 (291 km/h), Top right: Mons 2012 (294 km/h), Bottom left: Degrande 2001 (271 km/h), Bottom right: HS1 2012 (270 km/h)

6.3 Two layer model validation

The two layer ScopeRail model was also tested against the experimental data and the (Federal Railroad Administration, 2012) approach. Figure 16 shows that again both models over-predicted vibration levels. Despite this, ScopeRail performed with increased accuracy in comparison to when the homogenous soil profile was used. This is particularly clear for the Degrande 2001 results where a significant improvement is obtained (up to 9-10dB). For the Mons 2012 results enhanced accuracy was also found.

In comparison to the (Federal Railroad Administration, 2012) approach, ScopeRail was found to outperform it for the Mons 2012 and Degrande 2001 test sites, however performance was still low for both models at the HS1 2012 site. This increase in accuracy was attributed to the additional degrees of freedom available within the 2 layer ScopeRail model.

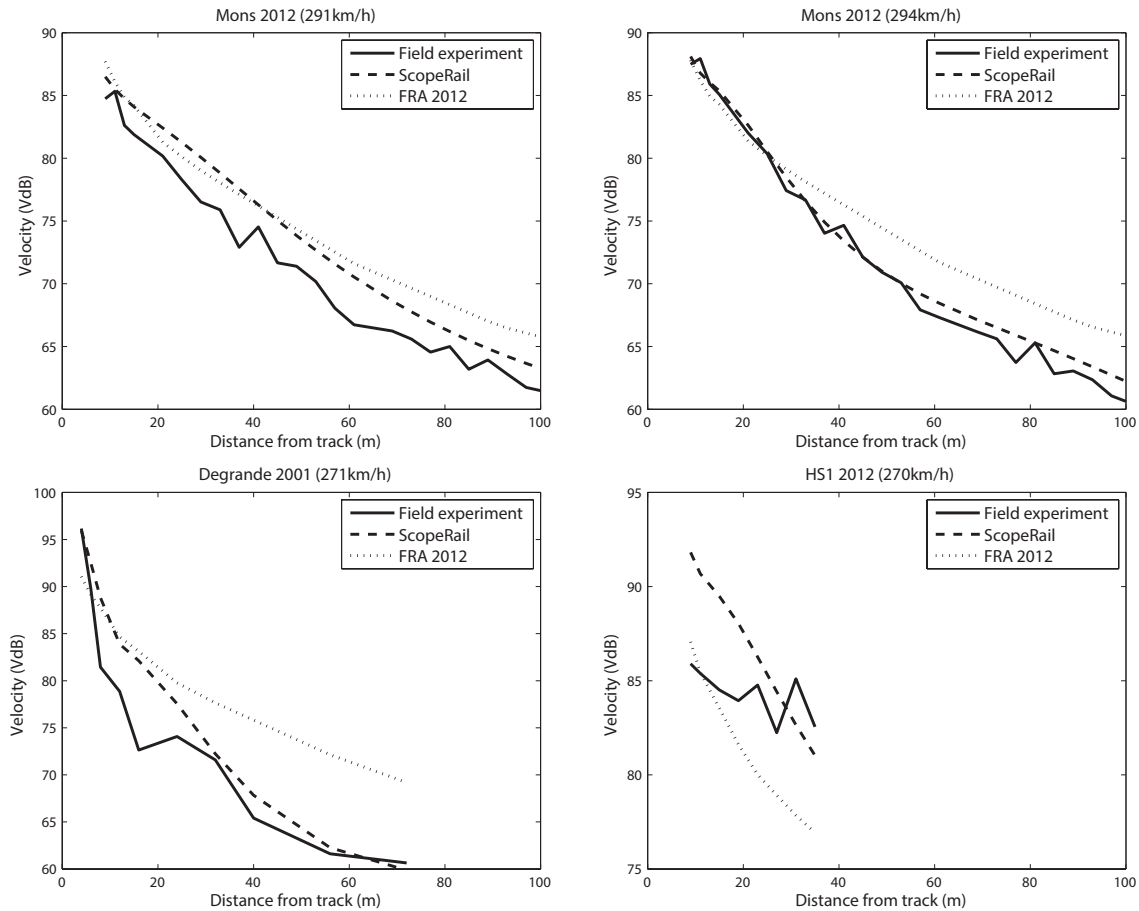


Figure 16 – Two layer model performance, Top left: Mons 2012 (291 km/h), Top right: Mons 2012 (294 km/h), Bottom left: Degrande 2001 (271 km/h), Bottom right: HS1 2012 (270km/h)

6.4 DISCUSSION

ScopeRail was found to offer strong vibration prediction performance, particularly when the 2 layer soil model was used. Prediction accuracy was highest for the Mons 2012 and Degrande 2001 test sites because the change in vibration levels with distance was relatively uniform, thus making these sites more straightforward to predict. In comparison, the HS1 2012 data set contained vibration levels with large amplitude unexpected local increases. It was challenging for the numerical model to predict these anomalies, however the scoping model was able to generate results that corresponded well to a best-fit line through the results. Therefore it was concluded that the new model offered improved performance in comparison to (Federal Railroad Administration, 2012).

7. CONCLUSIONS

A tool designed for the scoping assessment of in-door noise caused by high speed train passage was developed. Firstly, a three-dimensional numerical model capable of simulating vibration generation and propagation from high speed rail lines was outlined. This model was executed many times, each time using a different combination of input parameters, to create a database of results. These results were then analysed using a neural network approach to determine the effect of parameter changes on vibration levels. This resulted in a model that could instantly predict ground vibration levels in the presence of different train speeds and soil profiles. Finally, a collection of empirical factors were added to the model to facilitate the prediction of structural vibration and in-door noise in buildings located near high speed lines. The final model is called ScopeRail and was shown to offer increased accuracy over an alternative scoping model.

The advantage of this increased accuracy is that it reduces the probability of under and over prediction of vibration levels. If levels are over predicted then unnecessary detailed vibration assessments will be needed for further analysis. If levels are under predicted then abatement measures may be required post line construction. Therefore higher accuracy predictions can result in substantial cost savings.

8. ACKNOWLEDGEMENTS

The authors wish to thank the University of Edinburgh, the University of Mons and Heriot Watt University for the support and resources provided for the undertaking of this research. Additionally, the funding provided by Engineering and Physical Sciences Research Council (EP/H029397/1) and the Natural Environment Research Council is also greatly appreciated, without which, this research could not have been undertaken. It should also be noted that a selection of the experimental field results mentioned in this work can be found at www.davidpconnolly.com.

9. References

Andersen, L., Nielsen, S. R. K., & Krenk, S. (2007). Numerical methods for analysis of structure and ground vibration from moving loads. *Computers & Structures*, 85(1-2), 43–58. doi:10.1016/j.compstruc.2006.08.061

- Auersch, L. (2010). Building Response due to Ground Vibration — Simple Prediction Model Based on Experience with Detailed Models and Measurements. *International Journal of Acoustics and Vibration*, 15(3), 101–112.
- Auersch, L. (2012). Train induced ground vibrations: different amplitude-speed relations for two layered soils. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 226(5), 469–488. doi:10.1177/0954409712437305
- Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., & Presti, D. (1989). Modulus of sands from CPT's and DMT's. In *12th International conference on Soil Mechanics and Foundation Engineering* (pp. 165–170).
- Biglari, M., & Ashayeri, I. (2011). An empirical model for shear modulus and damping ratio of unsaturated soils. *Unsaturated Soils: Theory and Practice*, 1, 591–595.
- British Geological Association. (2013). Retrieved from <http://www.bgs.ac.uk/>
- Carels, P., Ophalffens, K., & Vogiatzis, K. (2012). Noise and Vibration evaluation of a floating slab in direct fixation turnouts in Haidari & Anthoupoli extensions of Athens metro lines 2 and 3. *INGEGNERIA FERROVIARIA*, 533–552.
- Chebli, H., Othman, R., Clouteau, D., Arnst, M., & Degrande, G. (2008). 3D periodic BE–FE model for various transportation structures interacting with soil. *Computers and Geotechnics*, 35(1), 22–32. doi:10.1016/j.compgeo.2007.03.008
- Chin, C., Duann, S., & Kao, T. (1988). SPT-CPT correlations for granular soils. In *1st International symposium on Penetration Testing* (pp. 295–339).
- Connolly, D., Giannopoulos, A., Fan, W., Woodward, P. K., & Forde, M. C. (2013). Optimising low acoustic impedance back-fill material wave barrier dimensions to shield structures from ground borne high speed rail vibrations. *Construction and Building Materials*, 44, 557–564. doi:10.1016/j.conbuildmat.2013.03.034
- Connolly, D., Giannopoulos, A., & Forde, M. C. (2013). Numerical modelling of ground borne vibrations from high speed rail lines on embankments. *Soil Dynamics and Earthquake Engineering*, 46, 13–19. doi:10.1016/j.soildyn.2012.12.003
- Connolly, D. P. (2014). High Speed Rail Dataset. Retrieved from <http://www.davidpconnolly.com/>
- Connolly, D. P., Kouroussis, G., Fan, W., Percival, M., Giannopoulos, A., Woodward, P. K., ... Forde, M. C. (2013). An experimental analysis of embankment vibrations due to high speed rail. In *Proceedings of the 12th International Railway Engineering Conference*.
- Connolly, D. P., Kouroussis, G., Giannopoulos, A., Verlinden, O., Woodward, P. K., & Forde, M. C. (2014). Assessment of railway vibrations using an efficient scoping model. *Soil*

Dynamics and Earthquake Engineering, 58, 37–47.
doi:10.1016/j.soildyn.2013.12.003

- Connolly, D. P., Kouroussis, G., Laghrouche, O., Ho, C., & Forde, M. C. (2014). Benchmarking Railway Vibrations - Track, Vehicle, Ground and Building Effects (accepted paper). *Construction and Building Materials - Special Issue: Railway Engineering*.
- Connolly, D. P., Peters, J., Sim, A., Giannopoulos, A., Forde, M. C., Kouroussis, G., & Verlinden, O. (2014). Railway vibration impact assessment-High accuracy and internationally compatible tool. In *Proceedings of the Transportation Research Board 93rd Annual meeting, Washington (USA)*.
- Costa, P. A., Calçada, R., & Cardoso, A. S. (2012). Ballast mats for the reduction of railway traffic vibrations. Numerical study. *Soil Dynamics and Earthquake Engineering*, 42, 137–150. doi:10.1016/j.soildyn.2012.06.014
- Degrade, G., & Schillemans, L. (2001). Free Field Vibrations During the Passage of a Thalys High-Speed Train At Variable Speed. *Journal of Sound and Vibration*, 247(1), 131–144. doi:10.1006/jsvi.2001.3718
- Dejong, J. (2007). *Site characterization - Guidelines for estimating Vs based on In-situ tests. Soil interaction laboratory, UCDavis* (pp. 1–22).
- Deutsches Institut für Normung. (1999). *DIN 4150-2 - Human exposure to vibration in buildings. International Standards Organisation* (pp. 1–63).
- Dickensen, S. (1994). *Dynamic response of soft and deep cohesive soils during the Loma Prieta earthquake of October 17, 1989. PhD thesis. University of California*.
- El Kacimi, A., Woodward, P. K., Laghrouche, O., & Medero, G. (2013). Time domain 3D finite element modelling of train-induced vibration at high speed. *Computers & Structures*, 118, 66–73. doi:10.1016/j.compstruc.2012.07.011
- Elias, P., & Villot, M. (2011). *Review of existing standards, regulations and guidelines, as well as laboratory and field studies concerning human exposure to vibration. Deliverable D1.4. (RIVAS)* (pp. 1–72).
- Federal Railroad Administration. (2012). *High-Speed Ground Transportation Noise and Vibration Impact Assessment. U.S. Department of Transportation* (pp. 1–248).
- Fiala, P., Degrade, G., & Augusztinovicz, F. (2007). Numerical modelling of ground-borne noise and vibration in buildings due to surface rail traffic. *Journal of Sound and Vibration*, 301(3-5), 718–738. doi:10.1016/j.jsv.2006.10.019
- Fryba, L. (1972). *Vibration of Solids and Structures Under Moving Loads* (pp. 1–524). Groningen, The Netherlands: Noordhoff International Publishing.

- Galvin, P., Romero, A., & Domínguez, J. (2010). Fully three-dimensional analysis of high-speed train-track-soil-structure dynamic interaction. *Journal of Sound and Vibration*, 329(24), 5147–5163. doi:10.1016/j.jsv.2010.06.016
- Griffin, M. (1998). A Comparison of Standardized Methods for Predicting the Hazards of Whole-Body Vibration and Repeated Shocks. *Journal of Sound and Vibration*, 215(4), 883–914. doi:10.1006/jsvi.1998.1600
- Gupta, S., Hussein, M., Degrande, G., Hunt, H. E. M., & Clouteau, D. (2007). A comparison of two numerical models for the prediction of vibrations from underground railway traffic. *Soil Dynamics and Earthquake Engineering*, 27(7), 608–624. doi:10.1016/j.soildyn.2006.12.007
- Hardin, B., & Black, W. (1963). Vibration modulus of normally consolidated clay. *Journal of the Soil Mechanics and Foundation Division*, 89, 33–65.
- Harris, Miller, & Hanson. (1996). *Summary of European high speed rail noise and vibration measurements (HMMH Report No. 293630-2)* (pp. 1–158).
- Hasancebi, N., & Ulusay, R. (2006). Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. *Bulletin of Engineering Geology and the Environment*, 66(2), 203–213. doi:10.1007/s10064-006-0063-0
- Hegazy, Y., & Mayne, P. (1995). Statistical correlations between Vs and CPT data for different soil types. In *(CPT'95), Symposium on Cone Penetration Testing* (pp. 173–178).
- Houbrechts, J., Schevenels, M., Lombaert, G., Degrande, G., Rucker, W., Cuellar, V., & Smekal, A. (2011). *Test procedures for the determination of the dynamic soil characteristics. (RIVAS - Deliverable D1.1)* (pp. 1–107).
- Hussein, M. F. M., & Hunt, H. E. M. (2007). A numerical model for calculating vibration from a railway tunnel embedded in a full-space. *Journal of Sound and Vibration*, 305(3), 401–431. doi:10.1016/j.jsv.2007.03.068
- Hussein, M. F. M., & Hunt, H. E. M. (2009). A numerical model for calculating vibration due to a harmonic moving load on a floating-slab track with discontinuous slabs in an underground railway tunnel. *Journal of Sound and Vibration*, 321(1-2), 363–374. doi:10.1016/j.jsv.2008.09.023
- Hussein, M., Hunt, H. E. M., Kuo, K., Costa, P. A., & Barbosa, J. (2013). The use of sub-modelling technique to calculate vibration in buildings from underground railways. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. doi:10.1177/0954409713511449
- Imai, T. (1977). P and S-wave velocities of the ground in Japan. In *Ninth International conference of Soil Mechanics and Foundation Engineering* (pp. 257–260).

- Imai, T., & Tonouchi, K. (1982). Correlation of N-value with S-wave velocity and shear modulus. In *Proceedings of the 2nd European symposium of penetration testing* (pp. 57–72).
- Ishibashi, I., & Zhang, X. (1993). Unified dynamic shear moduli and damping ratios of sand and clay. *Soils and Foundations*, 33(1), 182–191.
- Iyisan, R. (1996). Correlations between shear wave velocity and in-situ penetration test results. *Teknik Dergi*, 7(2), 1187–1199.
- Jafari, M., Shafiee, A., & Razmkhah, A. (2002). Dynamic properties of fine grained soils in south of Tehran. *Journal of Seismology and Earthquake Engineering*, 4(1), 25–35.
- Johnson, K. (1985). *Contact mechanics* (pp. 1–468). Cambridge, UK: Cambridge University Press.
- Kagawa, T. (1993). Moduli and damping factors of soft marine clays. *Journal of Geotechnical Engineering*, 118(9), 1360–1375.
- Katou, M., Matsuoka, T., Yoshioka, O., Sanada, Y., & Miyoshi, T. (2008). Numerical simulation study of ground vibrations using forces from wheels of a running high-speed train. *Journal of Sound and Vibration*, 318, 830–849. doi:10.1016/j.jsv.2008.04.053
- Kattis, S., Polyzos, D., & Beskos, D. (1999). Vibration isolation by a row of piles using a 3-D frequency domain BEM. *International Journal for Numerical Methods in Engineering*, 728(February), 713–728.
- Kenney, J. (1954). Steady-state vibrations of beam on elastic foundation for moving load. *Journal of Applied Mechanics*, 76, 359–364.
- Kouroussis, G., Connolly, D. P., Forde, M. C., & Verlinden, O. (2013). An experimental study of embankment conditions on high-speed railway ground vibrations. In *International congress on Sound and Vibration* (pp. 1–8). Bangkok, Thailand.
- Kouroussis, G., Connolly, D. P., Forde, M. C., & Verlinden, O. (2014). Train speed calculation using ground vibrations. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 0(0), 1–18. doi:10.1177/0954409713515649
- Kouroussis, G., Connolly, D. P., & Verlinden, O. (2014). Railway induced ground vibrations - a review of vehicle effects. *International Journal of Rail Transportation*, 2(2), 69–110. doi:10.1080/23248378.2014.897791
- Kouroussis, G., Verlinden, O., & Conti, C. (2011). Free field vibrations caused by high-speed lines: Measurement and time domain simulation. *Soil Dynamics and Earthquake Engineering*, 31(4), 692–707. doi:10.1016/j.soildyn.2010.11.012
- Kramer, S. (1996). *Geotechnical earthquake engineering* (pp. 1–653). Prentice Hall.

- Krylov, V. (1995). Generation of ground vibrations by superfast trains. *Applied Acoustics*, 44(2), 149–164. doi:10.1016/0003-682X(95)91370-I
- Larsson, R., & Mulabdic, M. (1991). Shear moduli in Scandinavian clays; measurements of initial shear modulus with seismic cones - empirical correlations for the initial shear modulus in clay. In *Transport Research Board* (pp. 1–127).
- Lee, C., & Tsai, B. (2008). Mapping Vs30 in Taiwan. *Terrestrial Atmospheric and Oceanic Sciences*, 19(6), 671–682. doi:10.3319/TAO.2008.19.6.671(PT)1.
- Lee, S. (1990). Regression models of shear wave velocities in Taipei basin. *Journal of the Chinese Institution of Engineers*, 13(5), 519–1990.
- Lombaert, G., & Degrande, G. (2009). Ground-borne vibration due to static and dynamic axle loads of InterCity and high-speed trains. *Journal of Sound and Vibration*, 319, 1036–1066. doi:10.1016/j.jsv.2008.07.003
- Lunne, T., Robertson, P., & Powell, J. (1997). *Cone penetrating testing* (pp. 1–312). Spon Press.
- Mayne, P. (2006). Undisturbed sand strength from seismic cone tests. *Geomechanics & Geoengineering*, 1(4), 239–257.
- Mayne, P., & Rix, G. (1993). Gmax-qc Relationships for Clays. *ASTM Geotechnical Testing Journal*, 16(1), 54–60.
- Mayne, P., & Rix, G. (1995). Correlations Between Shear Wave Velocity and Cone Tip Resistance in Clays. *Soils and Foundations*, 35(2), 107–110.
- Mulliken, J., & Rizos, D. C. (2012). A coupled computational method for multi-solver, multi-domain transient problems in elastodynamics. *Soil Dynamics and Earthquake Engineering*, 34(1), 78–88. doi:10.1016/j.soildyn.2011.10.004
- O'Brien, J., & Rizos, D. (2005). A 3D BEM-FEM methodology for simulation of high speed train induced vibrations. *Soil Dynamics and Earthquake Engineering*, 25, 289–301. doi:10.1016/j.soildyn.2005.02.005
- Ohta, Y., & Goto, N. (1978). Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthquake Engineering & Structural Dynamics*, 6(2), 167–187.
- Paoletti, L., Hegazy, Y., Monaco, S., & Piva, R. (2010). Prediction of shear wave velocity for offshore sands using CPT data – Adriatic sea. In *2nd International Symposium on Cone Penetration Testing* (pp. 1–8). Huntington Beach, California.
- Pitilakis, K., Raptakis, D., Lontzetidis, K., & T, T.-V. (1999). Geotechnical and geophysical description of EURO-SEISTEST, using field, laboratory tests and moderate strong motion recordings. *Journal of Earthquake Engineering*, 3(3), 381–409.

- Robertson, P., Campanella, G., & Wightman, A. (1983). SPT-CPT correlations. *Journal of Geotechnical Engineering*, 109(11), 1449–1459.
- Rollins, K., Evans, M., Diehl, N., & Daily, W. (1998). Shear Modulus And Damping Relationships For Gravels. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(5), 396–405.
- Rossi, F., & Nicolini, A. (2003). A simple model to predict train-induced vibration: theoretical formulation and experimental validation. *Environmental Impact Assessment Review*, 23(3), 305–322. doi:10.1016/S0195-9255(03)00005-2
- Seed, H., Idriss, I., & Arango, I. (1983). Evaluation Of Liquefaction Potential Using Field Performance Data. *Journal of Geotechnical Engineering*, 109, 458–482.
- Seed, H., Wong, R., Idriss, I., & Tokimatsu, K. (1987). Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils. *Journal of Geotechnical Engineering*, 112(11), 1016–1032.
- Sheng, X., Jones, C. J. C., & Petyt, M. (1999). Ground Vibration Generated By a Harmonic Load Acting on a Railway Track. *Journal of Sound and Vibration*, 225(1), 3–28. doi:10.1006/jsvi.1999.2232
- Sheng, X., Jones, C. J. C., & Thompson, D. J. (2004). A theoretical model for ground vibration from trains generated by vertical track irregularities. *Journal of Sound and Vibration*, 272(3-5), 937–965. doi:10.1016/S0022-460X(03)00782-X
- Sheng, X., Jones, C., & Thompson, D. (2006). Prediction of ground vibration from trains using the wavenumber finite and boundary element methods. *Journal of Sound and Vibration*, 293(3-5), 575–586. doi:10.1016/j.jsv.2005.08.040
- Sisman, H. (1995). *An investigation on relationships between shear wave velocity and SPT and pressuremeter test results (MSc thesis)*. Ankara University.
- Thornely-Taylor, R. M. (2004). The Prediction Of Vibration , Groundborne And Structure-Radiated Noise From Railways Using Finite Difference Methods – Part I - Theory. In *Proceedings of the Institute of Acoustics* (Vol. 26, pp. 1–11).
- Tsiambaos, G., & Sabatakakis, N. (2010). Empirical estimation of shear wave velocity from in situ tests on soil formations in Greece. *Bulletin of Engineering Geology and the Environment*, 70(2), 291–297. doi:10.1007/s10064-010-0324-9
- Vogiatzis, K. (2010). Noise & Vibration theoretical evaluation & monitoring program for the protection of the ancient “Kapnikarea Church” from Athens Metro Operation. *International Review of Civil Engineering (I.R.E.C.E.)*, 1(5), 328–333.
- Vogiatzis, K. (2012). Environmental ground borne noise and vibration protection of sensitive cultural receptors along the Athens Metro Extension to Piraeus. *Science of the Total Environment*, 439, 230–7. doi:10.1016/j.scitotenv.2012.08.097

Yang, L. A., Powrie, W., & Priest, J. A. (2009). Dynamic Stress Analysis of a Ballasted Railway Track Bed during Train Passage. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(5), 680. doi:10.1061/(ASCE)GT.1943-5606.0000032

Appendix

Source factor	Adjustment to ScopeRail results
Worn wheels of wheel flats	+ 10 dB
Worn or corrugated track	+ 10 dB
Crossovers or other special track work	+ 10 dB

Table A. 1 – ScopeRail source factors (replicated from (Federal Railroad Administration, 2012))

Track factor	Adjustment to ScopeRail results	
Floating slab track bed	- 15 dB	
Ballast Mats	- 10 dB	
High resilience fasteners	- 5 dB	
Resiliently supported sleepers	- 10 dB	
Type of track structure (relative to at-grade tie and ballast)	Ariel/Viaduct structure	- 10 dB
	Embankment	0 dB
	Open cutting	0 dB
Type of track structure (relative to bored tunnel in soil)	Station	- 5 dB
	Cut and cover	- 3 dB
	Rock-based	- 15 dB

Table A. 2 – ScopeRail track factors (replicated from (Federal Railroad Administration, 2012))

Receiver factor	Adjustment to ScopeRail results	
Coupling to building foundation	Wood frame	- 5 dB
	1-2 Story masonry	- 7 dB
	2-4 Story masonry	- 10 dB
	Large masonry (piled)	- 10 dB
	Large masonry (spread)	- 13 dB
	Foundation in rock	0 dB
Floor-to-floor attenuation	Storeys 1-5 above grade	- 2 dB per floor
	Storeys 5-10 above grade	- 1 dB per floor
Amplification due to resonances of floors, walls and ceilings	+ 6 dB	

Radiated sound	Typical at-grade track	- 50 dB
	Typical tunnelled track	- 35 dB
	Tunnel in rock	- 20 dB

Table A. 3 – ScopeRail receiver factors (replicated from (Federal Railroad Administration, 2012))